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A NUMERICAL STUDY OF THE THERMAL STABILITY OF SOLAR LOOPS

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Background

It has recently been shown that low-lying solar loops with apex heights $< 5\times10^3$ km admit a "cool" solution to the static energy and force balance equations, in addition to the familiar "hot" solution (Antiochos and Noci 1986). This cool solution reaches a maximum temperature of less than about 10^5 K, far below the million or so degrees of the hot solution. Both solutions are possible for a given amount of energy input to the loop. In hot loops much of the energy is conducted down to a thin transition region, where it is more easily radiated away, but in cool loops there is a much closer local balance between radiation and energy input, and conduction is relatively small.

With the exception of chromospheric features such as fibrils and filaments, the importance of cool loops on the Sun has yet to be established. Foukal (1975) discussed observations of loops cooler than 10^6 K, but such loops are not very common and are generally much hotter than 10^5 K. The possibility of cool loops in the range between 10^4 and 10^5 K has nonetheless stirred considerable interest, since an adequately large number of these loops could perhaps explain the well-known but not well-understood rise in emission measure for decreasing temperature below 10^5 K (Antiochos and Noci 1986; Dowdy, Rabin, and Moore 1986). Hot loops can satisfactorily reproduce the upper part of the observed emission measure curve, but they fail in the lower part where cool loops would be significant.

An important property of all loops is their thermal stability. If low-lying hot loops were thermally unstable, for example, we might expect a great majority of the low loops on the Sun to be cool. Indeed, theoretical studies suggest that very low-lying ($< 10^3$ km) hot loops are unstable to infinitely small perturbations (e.g., Antiochos et al. 1985). These studies fail to describe how the perturbations will behave in the nonlinear, physically observable regime, however. If the perturbations quickly saturate, then the loops are effectively stable.

The purpose of the work reported here is, first, to determine how small perturbations evolve in low-lying, linearly unstable hot loops, and second, to examine how high-lying, linearly stable hot loops respond to large amplitude disturbances such as might be expected on the Sun. Only general descriptions and results are given here. Details will be provided in a forthcoming paper (Klimchuk, Antiochos, and Mariska 1986).

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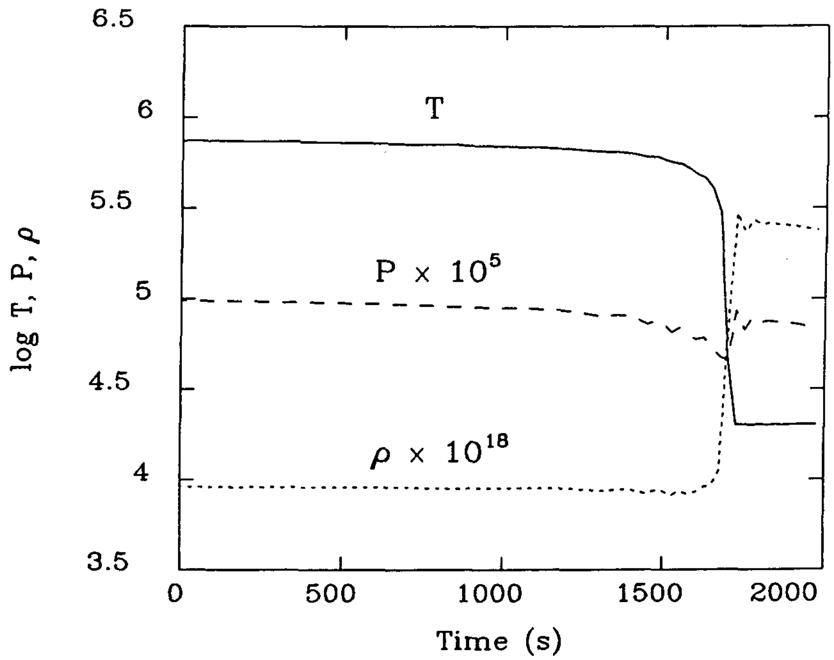

Figure 1. The evolution of temperature, pressure, and density at the top of the low-lying loop. Units are in the cgs system. Note that the vertical scale is logarithmic.

Numerical Simulations

The computer model we use to address these issues solves the time-dependent equations of mass, momentum, and energy transport for a fully ionized solar plasma confined to a rigid magnetic flux tube. The tube consists of a semi-circular coronal loop which extends deep into a 2×10^4 K chromosphere. We assume uniform energy input per unit volume, constant cross-sectional area, and the radiation law of Raymond modified by a T^3 dependence below 10^5 K. If anything, these assumptions should have a stabilizing influence on the atmosphere. The spatial resolution of the finite difference grid ranges from 1 km in the transition region to 100 km in the upper corona.

We first consider a low-lying loop with an apex height of 500 km above the chromosphere (in the regime of linear instability). Small imperfections in the initial static "equilibrium" are allowed to evolve. Figure 1 shows the variation of temperature, pressure, and density at the top of the loop. A very slow cooling takes place during the first 1650 s, but then the temperature plummets dramatically from 4×10^5 to 2×10^4 K in matter of less than a minute. Densities increase by a comparable amount during this time, so the pressure is approximately constant. Eventually the transient flows which are created die down and the atmosphere settles into a new static equilibrium. It is a cool equilibrium of the type discussed by Antiochos and Noci (1986). Because of the very low temperatures, however, the state of the loop is best described as an "extended chromosphere."

Closer examination of the calculations reveals that the rapid cooling phase seen in Figure 1 occurs throughout the simulation, but at progressively higher locations within the loop. At all times the plasma at lower transition zone temperatures cools very quickly and condenses onto the chromospheric interface. This interface moves upward, partially from the accumulation of new material, but mostly because the chromosphere expands in response to gradually decreasing pressures in the overlying corona. The expansion finally reaches the top of the loop at a time of about 1700 s into the simulation. In some sense the chromosphere appears to "eat away" at the slowly cooling corona from below. We can understand this evolution in terms of a succession of quasi-static equilibria, each of which is destroyed by the nonlinear growth of its fundamental eigenmode (Klimchuk, Antiochos, and Mariska 1986). These eigenmodes are sharply peaked near $4x10^4$ K, where most of the evolution takes place.

We next consider a much larger loop with an apex height of 10^4 km. Linear theory predicts it to be stable. In agreement with this theory, the loop does not respond to imperfections in the initial equilibrium other than by adjusting very slightly to achieve the true equilibrium. We have simulated the response of this loop to perturbations as large as 20 %. Both short and long wavelength disturbances were considered. The short wavelength disturbance has the form of the least stable (fundamental) eigenmode, and the long wavelength disturbances have the form of quarter sine waves extending from the top of the loop through most of the corona. The latter are characterized by either constant pressure or constant density. In each case the loop atmosphere appears to be returning to its original hot state after the perturbation is applied. There is no evidence for evolution to a new cool state or a highly dynamic hot state.

Discussion

The outcomes of our numerical simulations suggest two important results concerning the stability of hot coronal loops: 1) low-lying loops with apex heights less than about 10^3 km are nonlinearly unstable to small amplitude perturbations; and 2) high-lying loops with apex heights greater than about $5x10^3$ km are stable to all reasonable perturbations, including those of large amplitude and long wavelength. The latter conclusion was reached independently by other investigators (e.g., Peres et al. 1982). These results are fully consistent with the most recent linear theory (Antiochos and An 1987). By showing that unstable linear perturbations are able to grow without saturation, we have extended the theory into the realm of physical observation.

The potential implications of these results are severalfold. First, high-lying hot loops can be in a static or nearly static state if the applied perturbations are of small enough amplitude; dynamical motions need not be a fundamental property of all loops. The motions that have been observed (e.g., Brueckner 1980) seem to imply large amplitude disturbances of the type discussed above, or, more likely, large changes in the heating rate as discussed elsewhere in these Proceedings by Mariska.

A second implication is that the hot state should not occur frequently in very low-lying loops on the Sun. Since low-lying magnetic fields are known to be common (e.g., Giovanelli 1980), we might therefore expect cool loops to be very abundant. This could perhaps explain the emission measure puzzle discussed above. A difficulty with this picture, however, is that the hot loops which are linearly unstable are so low-lying ($<10^3$ km) and their cool state may be not much more than an extended chromosphere. The more interesting cool states with temperatures approaching 10^5 K would then occur only in loops of greater height.

For a roughly uniform heating, cool loops are possible up to a height of a few thousand kilometers. We can therefore identify an intermediate height range in which cool states exist and the corresponding hot states are linearly stable. The mere existence of an alternate state suggests that the hot state in these loops might be unstable to large amplitude disturbances. We have tested this hypothesis on a 2×10^3 km loop and find that the hot state is, in fact, stable to such disturbances. Thus, if 10^5 K cool loops exist on the Sun, they must be formed in that state initially; apparently then cannot easily evolve from preexisting hot loops.

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References

Antiochos, S. K., Shoub, E. C., An, C.-H., and Emslie, A. G. 1985, Ap. J., **298**, 876.

Antiochos, S. K., and Noci, G. 1986, Ap. J., **301**, 440.

Antiochos, S. K., and An, C.-H. 1987, in preparation.

Brueckner, G. E. 1980, in Highlights of Astronomy, vol. 5, ed. P. A. Wayman (Dordrecht: D. Reidel), p. 557.

Dowdy, J. F., Jr., Rabin, D., and Moore, R. L. 1986, Solar Phys., **105**, 35.

Foukal, P. V. 1975, Solar Phys., **43**, 327.

Giovanelli, R. G. 1980, Solar Phys., **68**, 49.

Klimchuk, J. A., Antiochos, S. K., and Mariska, J. T. 1986, submitted to Ap. J.

Peres, G., Rosner, R., Serio, S., and Vaiana, G. S. 1982, Ap. J., **252**, 791.